AN2459
Application note

Digital Power Factor Correction for Tube Lamp Ballasts and other digital power supplies controlled by an 8-bit microcontroller

1 Introduction

The electronic ballast market has undergone dramatic changes over the last few years. It has moved from full analog, very differentiated applications made by a collection of drivers and controllers, where use of custom ASICs was widespread, to a couple of standard platforms.

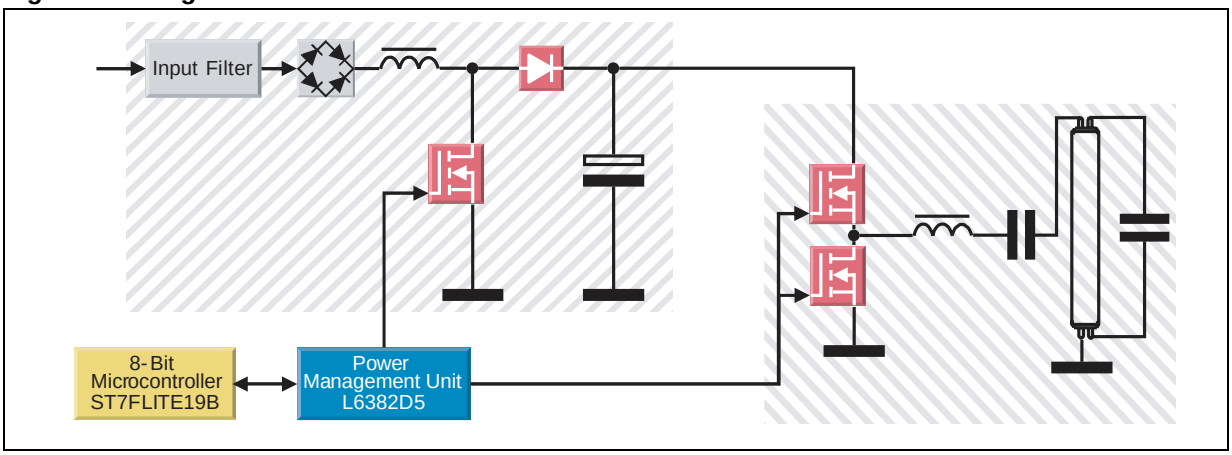
The basic building blocks are still the same. They include a power factor corrector stage and an inverting high voltage stage (*Figure 1*). On the one hand, analog platforms are targeting the low cost/basic performance applications. Their main drivers and controllers are widely used and well known ICs such as Power Factor Correctors (L6561/2/3) and High Voltage Ballast Controllers (L6569x/ L6571x/ L6574). On the other hand, a new digital platform concept has gained more interest and acceptance. A microcontroller with a simple Half Bridge Driver (L638x) has replaced the ballast controller. The Half Bridge Driver is used mainly for high-end applications, especially where the microcontroller has to deal with communication tasks (e.g. using the Dali protocol).

STMicroelectronics' digital ballast reference design STEVAL-ILB002V1 introduces a safe operating Power Factor Controller (PFC) and Ballast Controller. Even with relatively simple microcontroller firmware routines, the results for power control and ballast protection are in line with advanced analog controlled ballasts, while adding flexibility, for example, the possibility to drive a wide variety of lamps, or to easily introduce different protection schemes.

This application note deals in detail with the first block of the digital ballast, which provides stable DC bus voltage for the halfbridge in all load conditions, as well as controlling the input current shape which fulfills IEC standards (*6.: IEC 61000-3-2 "Electromagnetic compatibility".*).

The final description of the digital ballast - the lamp control block - will be described in detail in a separate application note.

Figure 1. Digital ballast scheme



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2 Power Factor Correction (PFC)

Theoretically, any switching topology can be used to achieve a high power factor but, in practice, the boost topology has become the most popular because of the advantages it offers. These include:

- Circuit requires the least external parts, thus it is the cheapest available.
- Boost inductor, located between the bridge and the switch, lowers the input di/dt, thus minimizing noise generated at the input and consequently reducing the EMI filter input requirements.
- Switch is source-grounded and therefore easy to drive.

Three methods of controlling the PFC preregulator are currently widely used. They are:

- The Fixed Frequency Average Current Mode PWM.
- The Transition Mode (TM) PWM (fixed on-time, variable frequency).
- The peak current mode with fixed off-time.

Control of the first method is complicated and requires a sophisticated IC controller (e.g. either ST's L4981A or ST's L4981B which offers frequency modulation) and a considerable component count.

Control of the second method is simpler (e.g. ST's L6561/2/3 family) and requires fewer external parts. It is therefore much less expensive.

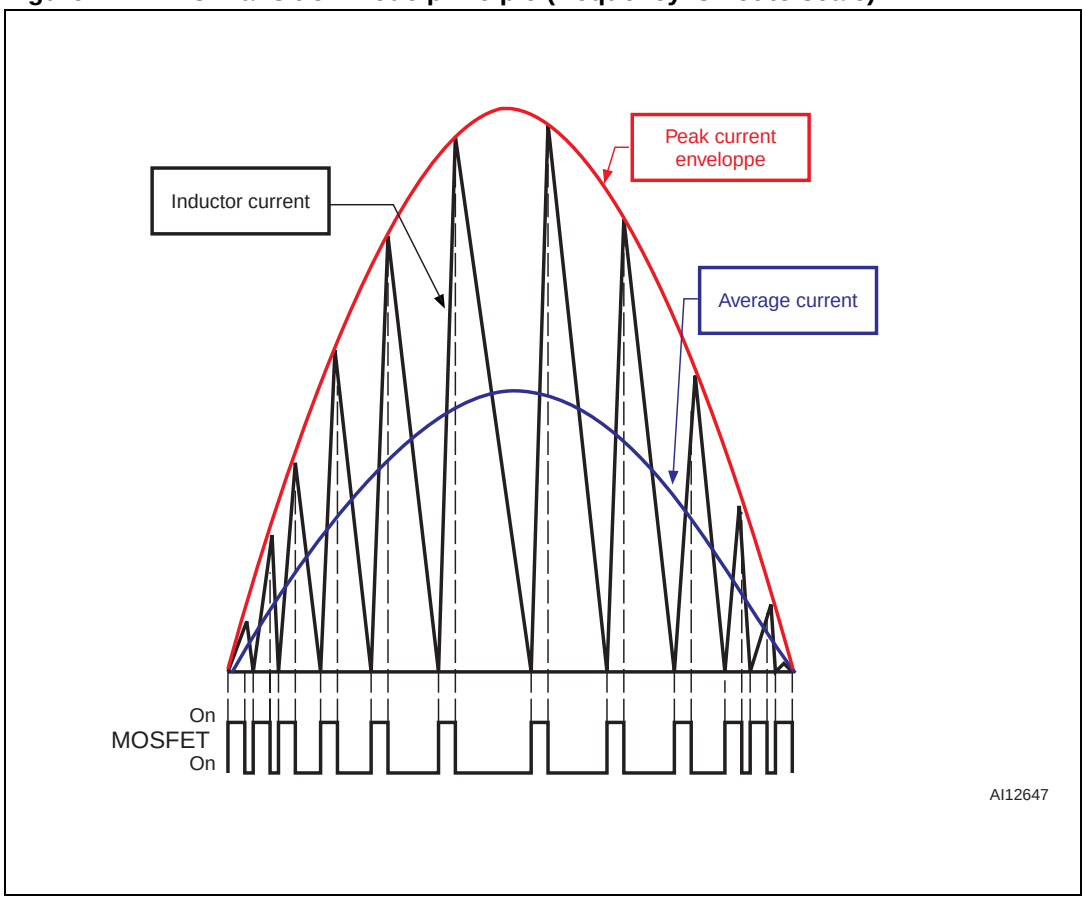
With the Fixed Frequency Average Current Mode method, the boost inductor operates in continuous conduction mode, while the TM method causes the inductor to work on the boundary between continuous and discontinuous modes. Thus, for a given throughput power, TM operation involves higher peak currents, suggesting it is more efficient at lower power ranges (typically below 200W). In contrast, the Fixed Frequency Average Current Mode is recommended for higher power levels.

A third method of control, that of applying constant. Toff control, results in continuous conduction mode. The same simple TM-controllers may be used, as may a small RC network to set the off-time. This method is described in AN1792 (*7*) It is optimal for an input power of between 200 and 400W.

2.1 Transition Mode operation

As mentioned above, the typical PFC topology used in electronic ballasts is a step-up (boost) regulator (*Figure 1*) working in transition conduction mode. *Figure 2* outlines the Transition Mode principles. When the MOSFET is turned on, the inductor is charged from the input voltage source. When the MOSFET is turned off, the boost inductor discharges its energy into the load until its current falls to zero. When the latter occurs, the boost inductor has no energy and a zero current (ZCD) signal is detected, due to a demagnetization change on the auxiliary winding. This drives the MOSFET on again, whereby another conversion cycle starts. As the drain voltage drops before turn-on, the turn-on switching losses are minimized. *Figure 2* indicates the geometric relationship of average and peak currents. Due to the triangular shape of the inductor current, the peak current is twice the average current.

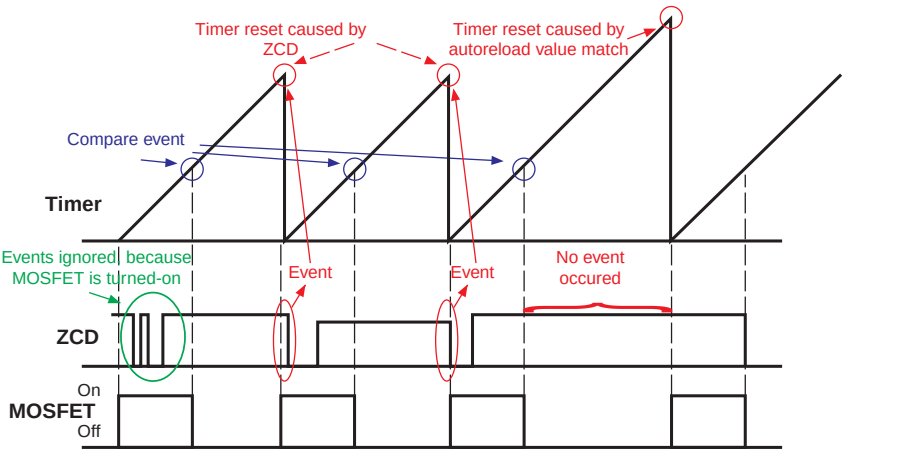
Figure 2. PFC Transition Mode principle (frequency is not to scale)



2.2 Digital implementation - Enhanced One Pulse Mode

To provide good switch control, as described in *Chapter 2.1* above, a simple 8-bit microcontroller may be used and a special PWM timer mode has been introduced. The timer mode, called "Enhanced One Pulse Mode" of the PWM generator (12-bit autoreload timer) is found inside the ST7FLITE19B microcontroller. It is explained in *Figure 3* and in datasheet ST7Lite1xB (*4*). In principle, when a zero current event occurs the microcontroller will reset the timer and turn-on the PFC MOSFET. If there is no signal from ZCD, the timer will overflow and turn-on the MOSFET anyway (it means a minimum switching frequency is secured). The on-time of the MOSFET is set by a software control routine and is constant during the mains half-cycle (this is detailed below in *Chapter 4*). The control routine executed by the MCU alters the on-time depending on the input voltage level and the load current.

Figure 3. Principle of the Enhanced One Pulse Mode, inside the ST7Lite1B



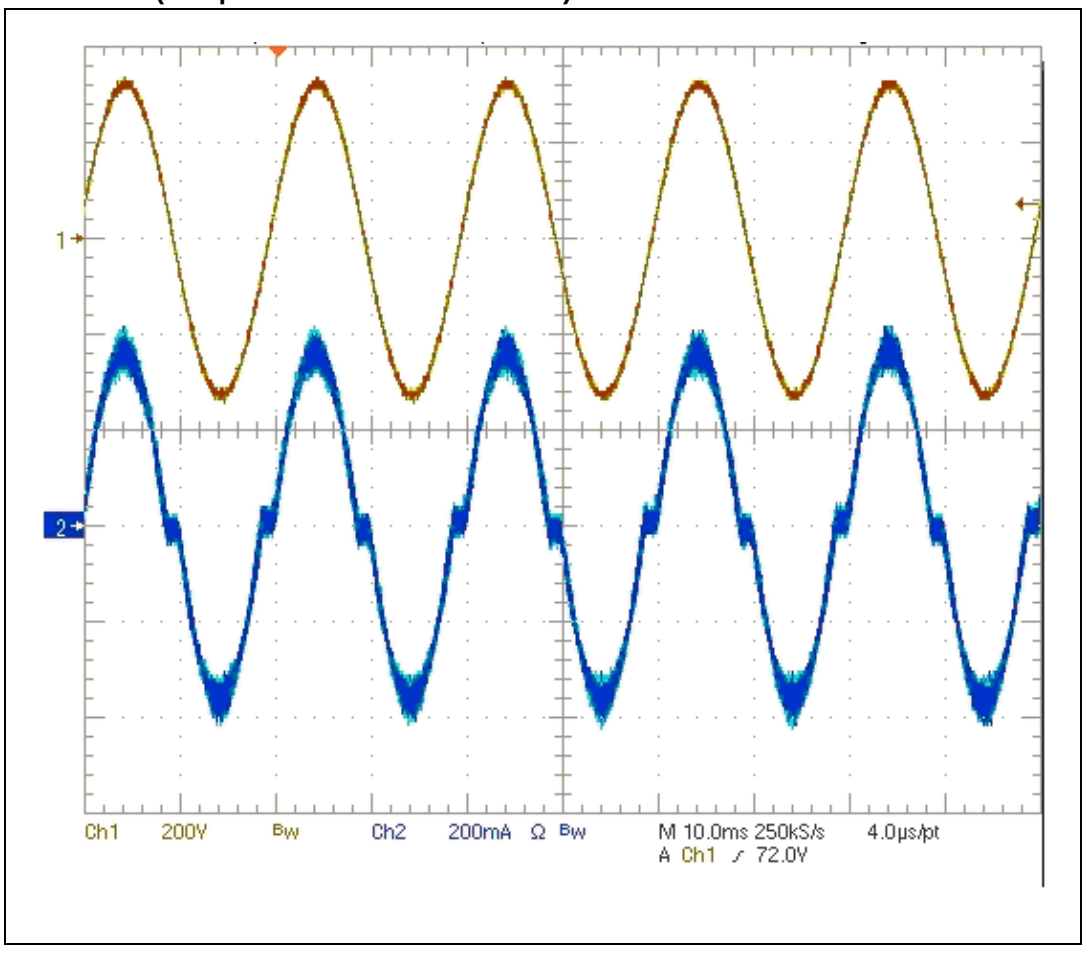
3 Power circuits design

3.1 Power components

All components have been calculated following application note AN966 (*3*). A full description of the design and selection of each component, based on the analog TM PFC controller L6561, is also given in *Appendix A*. At the moment, input voltage is limited for European mains. Future Software updates will include wide range input capability.

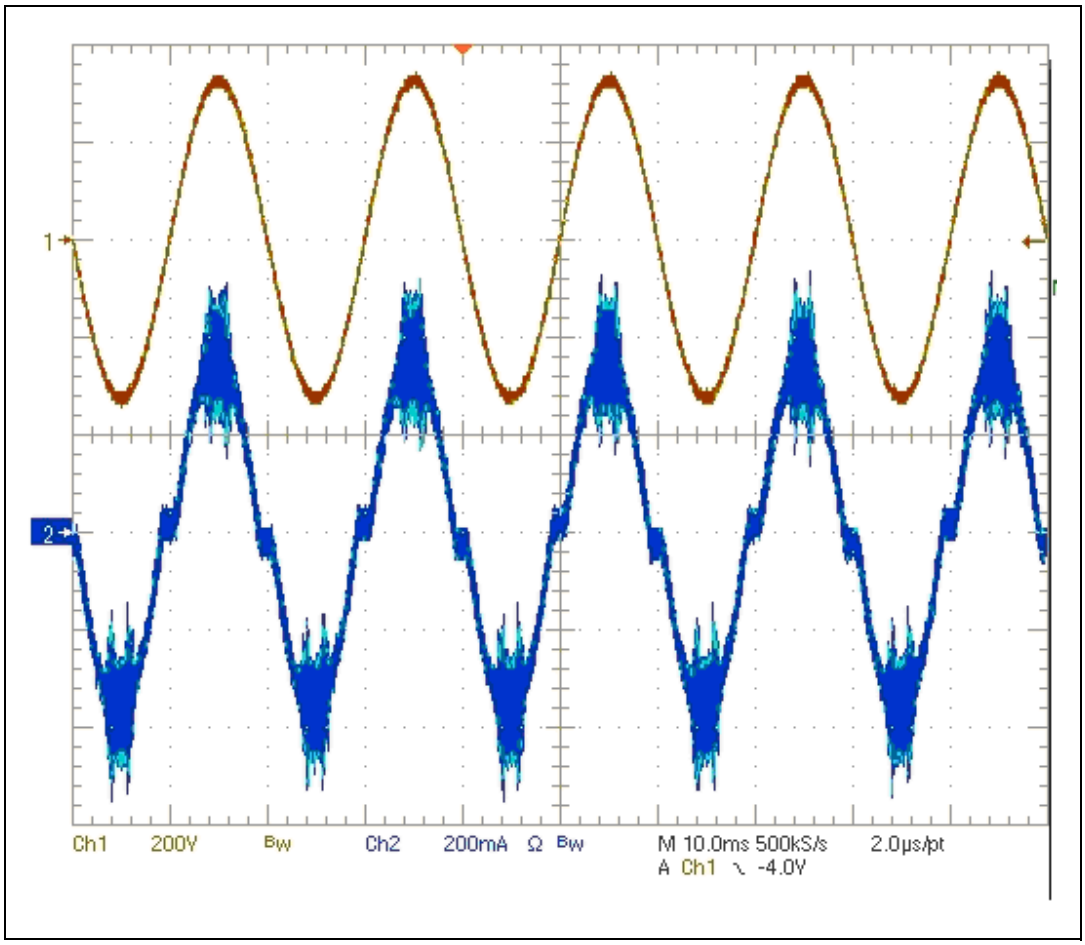
Besides the passive and discrete components of the microcontroller, the most important part is the power management unit, L6382D5, which helps control the power. It provides a stable (±2%) 5V supply for the microcontroller during the whole operation. It also supplies a high voltage start-up. In addition, one of the general purpose gate drivers integrated inside L6382D5 is used to translate TTL PWM signals from the microcontroller to the boost converter gate of the MOSFET.

Figure 4. Input voltage & current with modified EMI filter (compared to STEVAL-ILB002V1) PF = 0.994 THD = 10.3%



Note: Brown = Mains voltage, Blue = Input current.

Figure 5. Input voltage & current measured on STEVAL-ILB002V1 (old EMI filter) PF = 0.991 THD = 10.4%



Note: Brown = Mains voltage, Blue = Input current.

Reference board design measurements of STEVAL-ILB002V1(*Figure 5*) show a THD value of 10.4% and a PF value of 0.991. Between the manufacturing of the STEVAL-ILB002V1 reference design and publication of this application note, design work has continued and some improvements have been made. For example, EMI filter parameters have been changed from C-L-C to C-L filters, which give better results for waveform, power factor, and THD .This optimized version is given in *Figure 7* and result in the measured waveforms shown in *Figure 4* with THD = 10.3% and PF = 0.994.

3.2 Schematics

Figure 6. Schematics of STEVAL-ILB002V1 reference design

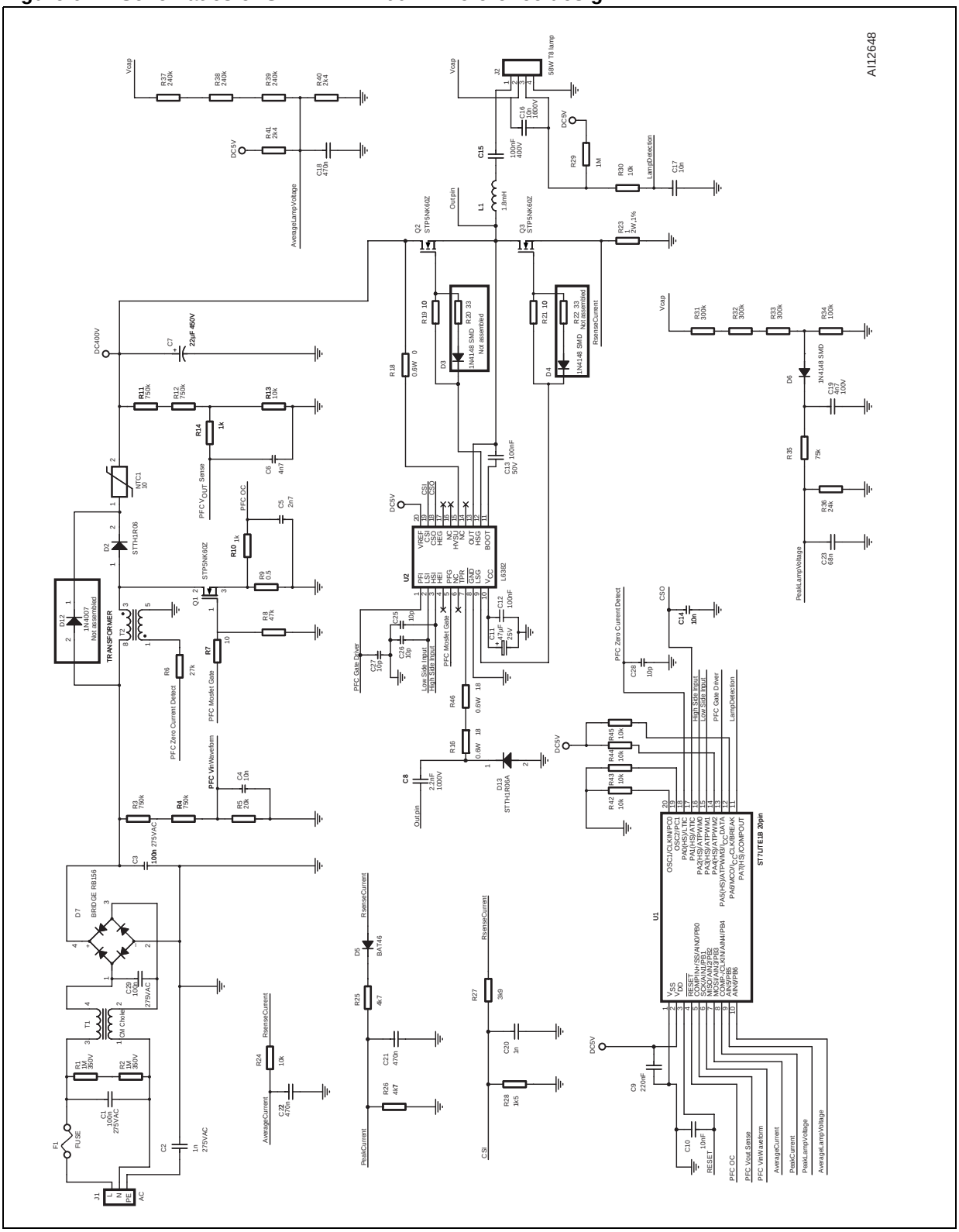
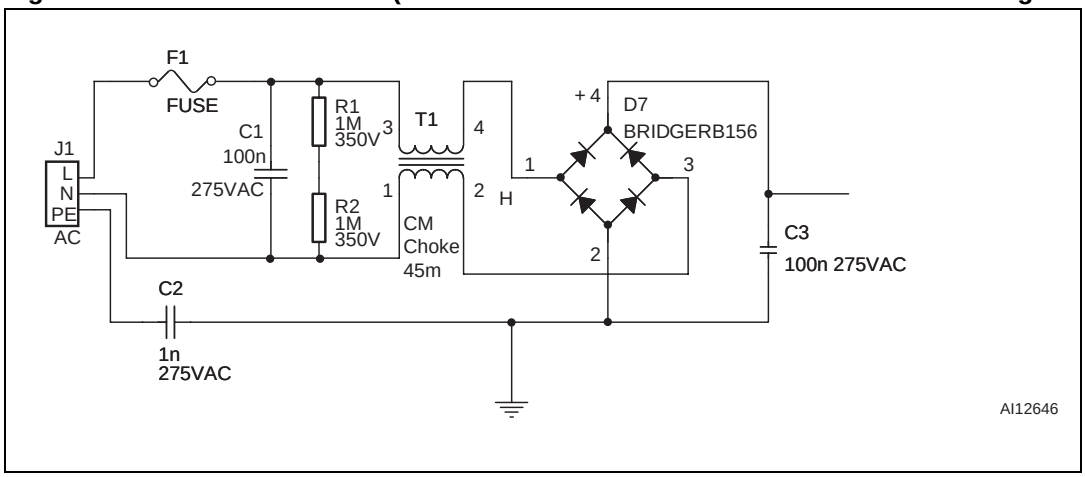


Figure 7. Modified EMI filter (not included in STEVAL-ILB002V1 reference design



3.3 Bill of material (STEVAL-ILB002V1)

Table 1. Bill of material - PFC

Reference	Part	Description	Supplier	Order code
C2	2.2n	X1,Y2 ceramic capacitor		
C1, C3	100n 400V	X2 capacitor		
C4	10n	SMD 0805		
C5	2n7	SMD 0805		
C6	4n7	SMD 0805		
C7	22µF	Elyt 450V		
C27	10p	SMD 1206		
D7	Bridge	1.5A 600V		
D12	1N4007	Not assembled		
F1	FUSE	Roundfuse 2A 250V		
NTC1	10	NTC 5R		
Q1	STP5NK60Z	TO 220	STMicroelectronics	STP5NK60Z
R1,R2	1M 200V	SMD 1206		
R3, R4, R11, R12	750k	SMD 1206 200V		
R5	20k	SMD 1206		
R6	27k	0.6W, THT 0207		
R7	10	SMD 1206		
R8	47k	SMD 1206		
R9	0.5	SMD 2512 2W 1%		
R10, R14	1k	SMD 1206		
R13	10k	SMD 1206		
T1	Common mode choke	Murata		
T2	Transformer	0.8mH primary	Vogt	5753201600
J1	Connector	ARK500/3		

Table 2. Bill of material - Lamp Control

Reference	Part	Description	Supplier	Order code
C10	10nF	SMD 0805		
C13	100nF	SMD 1206 50V		
C14	10n	SMD 0805		
C15	100nF	400V open case		
C16	10n	1600V		
C17	10n	SMD 1206		
C18, C21, C22	470n	SMD 0805, 16V		
C19	4n7 100V	SMD 1206		
C25, C26, C28	10p	SMD 0805		
C20	1n	SMD 0805		
C23	68n	SMD 0805		
D2	STTH1R06	DO-41 ultrafast diode	STMicroelectronics	STTH1R06
D3, D4	1N4148	Not assembled		
D6	1N4148	SMD SOD80		
D5	BAT46	SOD 323	STMicroelectronics	BAT46J
J2	Connector	ARK500/2		
L1	1.8m	COIL	Vogt	SL 041 123 31 02
Q2, Q3	STP5NK60Z	TO 220	STMicroelectronics	STP5NK60Z
R29	1M 200V	SMD 1206		
R30	10k	SMD 1206		
R19, R21	33	SMD 1206		
R20, R22	33	Not assembled		
R23	1	1W, SMD 2512, 5%		
R24, R42, R43, R44, R45	10k	SMD 0805		
R25,R26	4k7	SMD 0805		
R27	3k9	SMD 0805		
R28	1k5	SMD 0805		
R31,R32,R33,	300k	0.6W, THT 0207, 300V		
R34,	100k	0.6W, THT 0207, 300V		
R35	75k	SMD 1206, 200V		
R36	24k	SMD 1206		
R40	2k4	0.6W, THT 0207, 300V		
R41	2k4	SMD 1206		
R37,R38, R39	240k	0.6W, THT 0207, 300V		

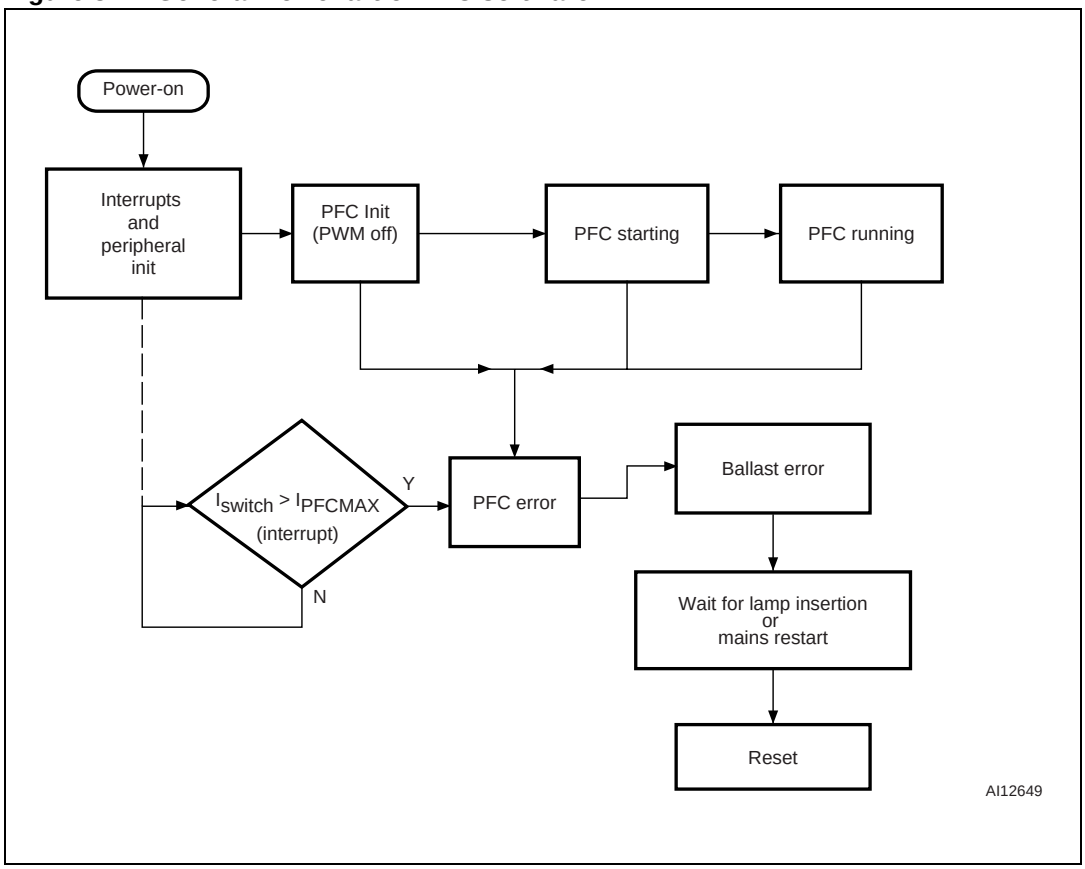
Table 3. Bill of material - general

Reference	Part	Description	Supplier	Order code
C8	2.2nF	Y1		
R16,R46	18	0.6W, THT 0207		
R18	0	0.6W, THT 0207		
D13	STTH1R06A	SM-A	STMicroelectronics	STTH1R06A
C11	47µF	Elyt 35V		
C12	100nF	SMD 1206		
U1	ST7LITE1B 20pin	DIP 20	STMicroelectronics	ST7FLIT19BF1B6
U2	L6382D5	SO 20	STMicroelectronics	L6382D5

4 Signals measurement, processing & control

Figure 8 shows the general flow diagram of the PFC Software. It is described in a step by step fashion in the following paragraphs.

Figure 8. General flowchart of PFC software



4.1 Input voltage

The first signal used by the microcontroller is a voltage connected to the input connector. This voltage is first divided and filtered by the circuitry shown in *Figure 9*. Then it is measured by an analog to digital converter (ADC) inside the microcontroller. This signal has several uses. The first is to avoid connecting the wrong input voltage at the beginning (i.e. only European mains are allowed) and second to guard input over-voltage during normal operation. The whole operation is stopped if the microcontroller detects any problems. If an application is stopped due to a fail condition, it could be restarted only by re-lamping (insertion of the lamp) or by mains recycling. The third use of the input voltage measurement is to detect this recycling (disconnection and reconnection of the mains).

A fourth use of the input voltage is when it works in conjunction with the main control loop (described in *Chapter 4.2*) to recognize a zero mains voltage crossing.

Figure 9. Input voltage sensing circuit

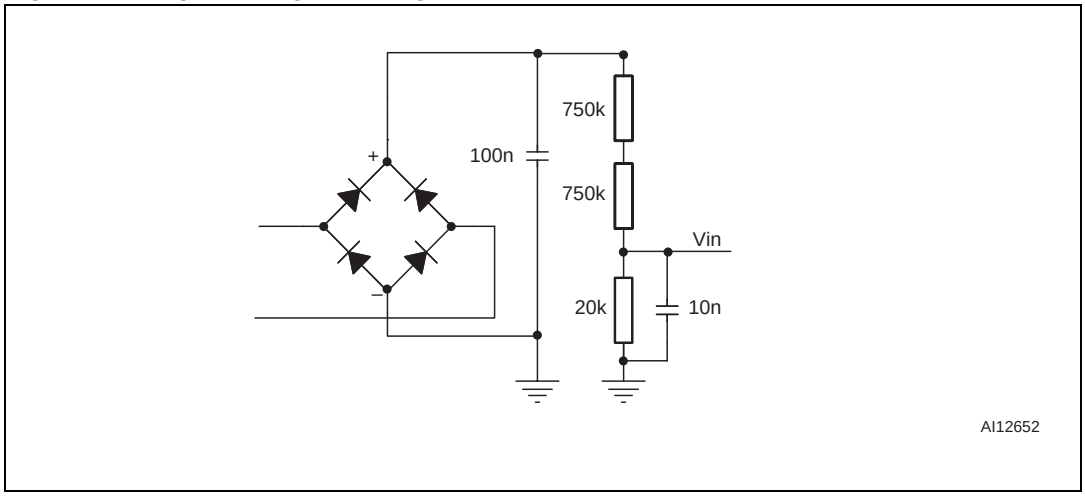
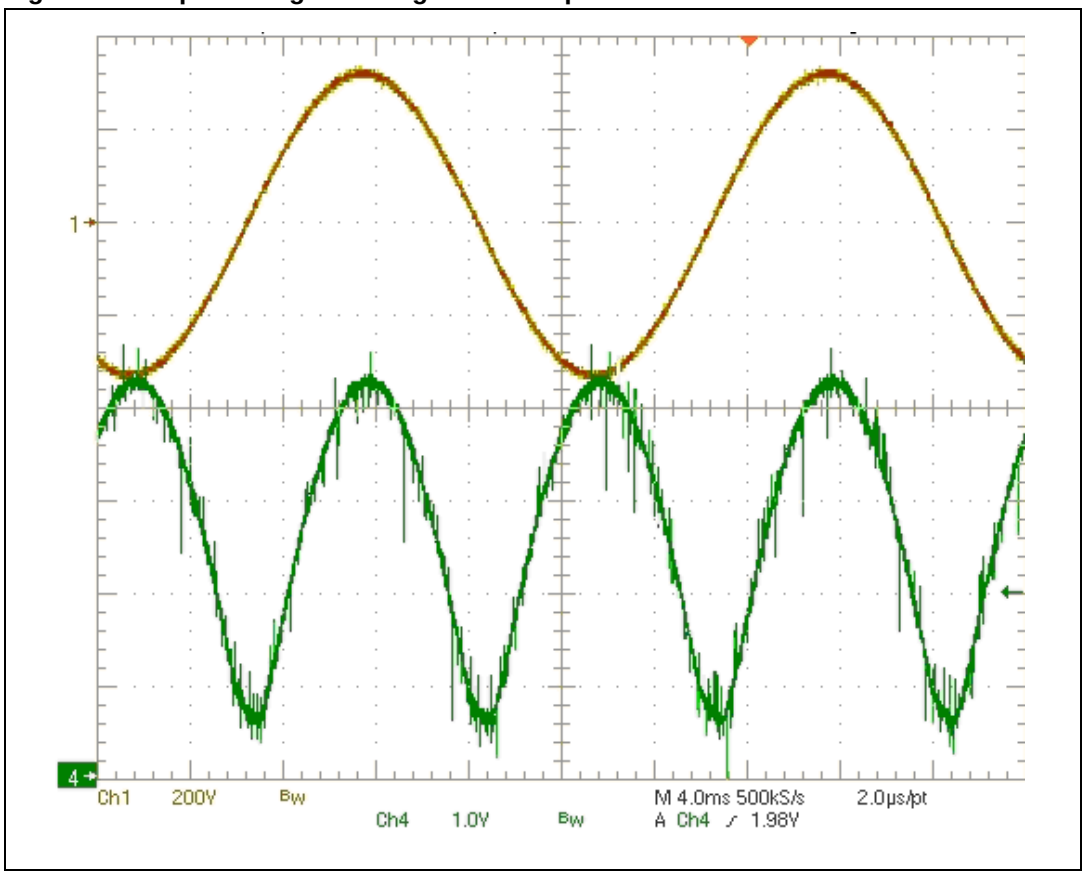
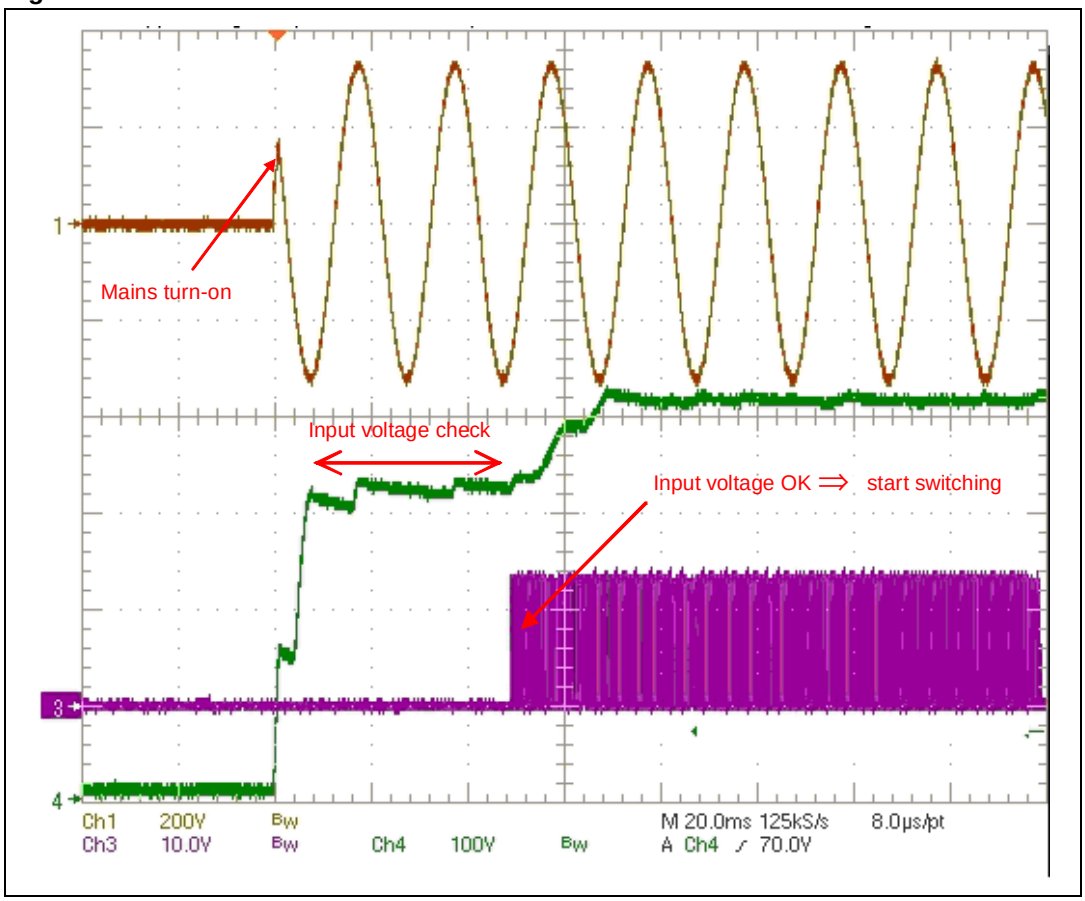


Figure 10. Input voltage sensing circuit output



Note: Brown = mains voltage, Green = voltage on ADC pin.

Figure 11. The mains turn-on



Note: Brown = mains, Green = DC output, Purple = PFC MOSFET gate.

4.2 Output voltage

The DC bus voltage (PFC output voltage) is measured by a high voltage divider with a low-pass filter (*Figure 12*). It is used by the software as an input for a PID regulator to calculate the MOSFET on-time. Parameters for the regulator are not fixed but change depending on the lamp state. This is because the electronic ballast behaves like a load with strongly changing conditions (preheating / ignition / normal operation). *Figure 13* outlines one control cycle, and clearly shows that the regulator changes the MOSFET on-time at the synchronization event with the mains voltage zero crossing.

Figure 12. Output voltage sensing circuit

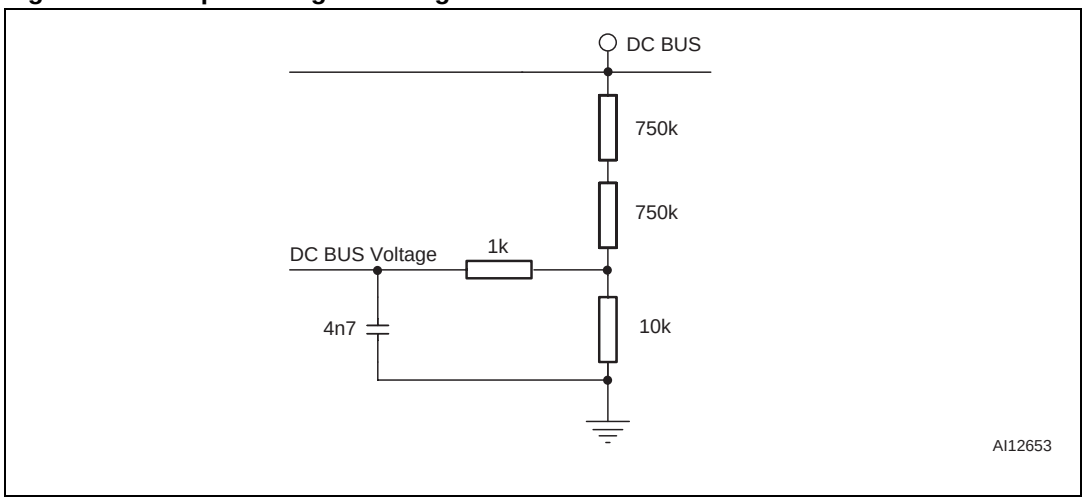


Figure 13. Output voltage control loop flowchart

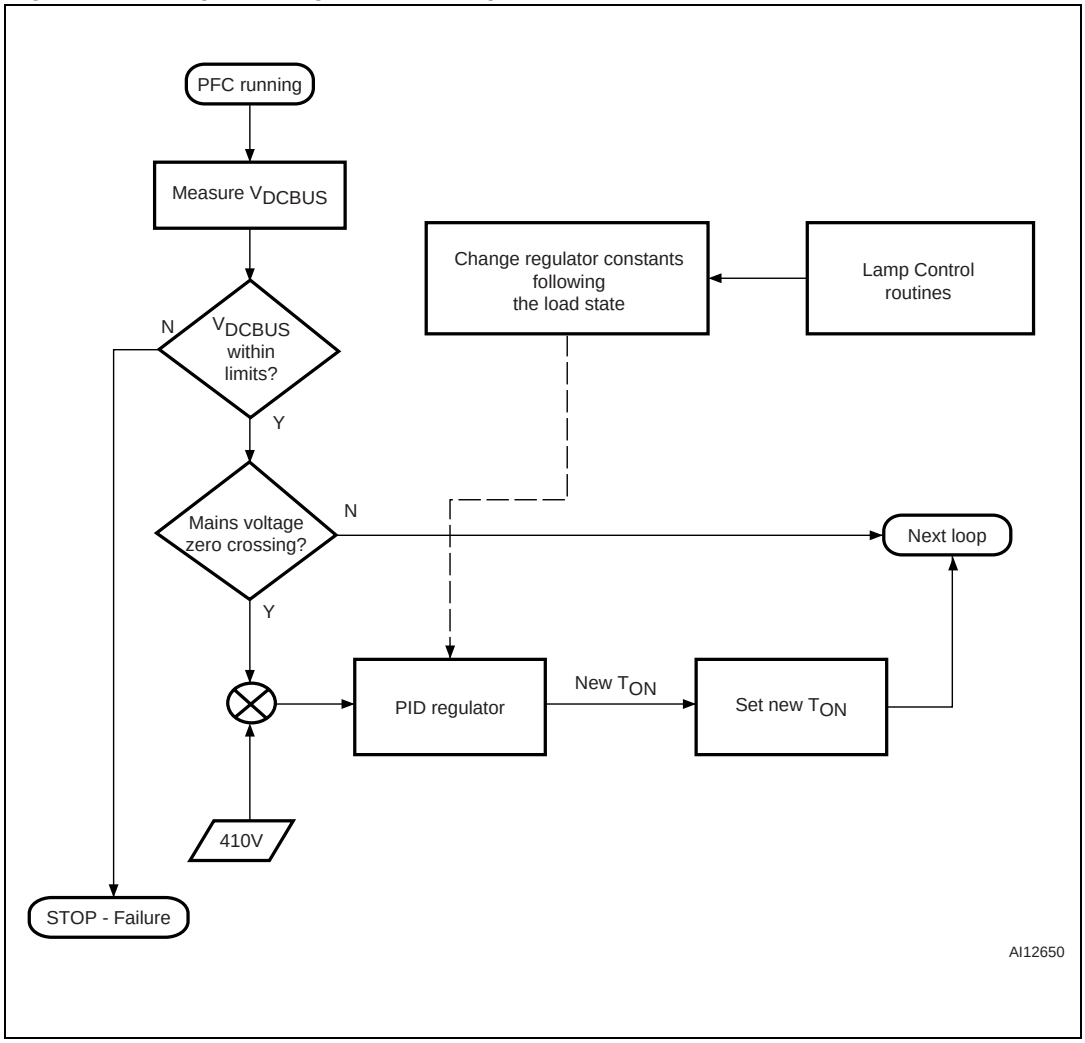
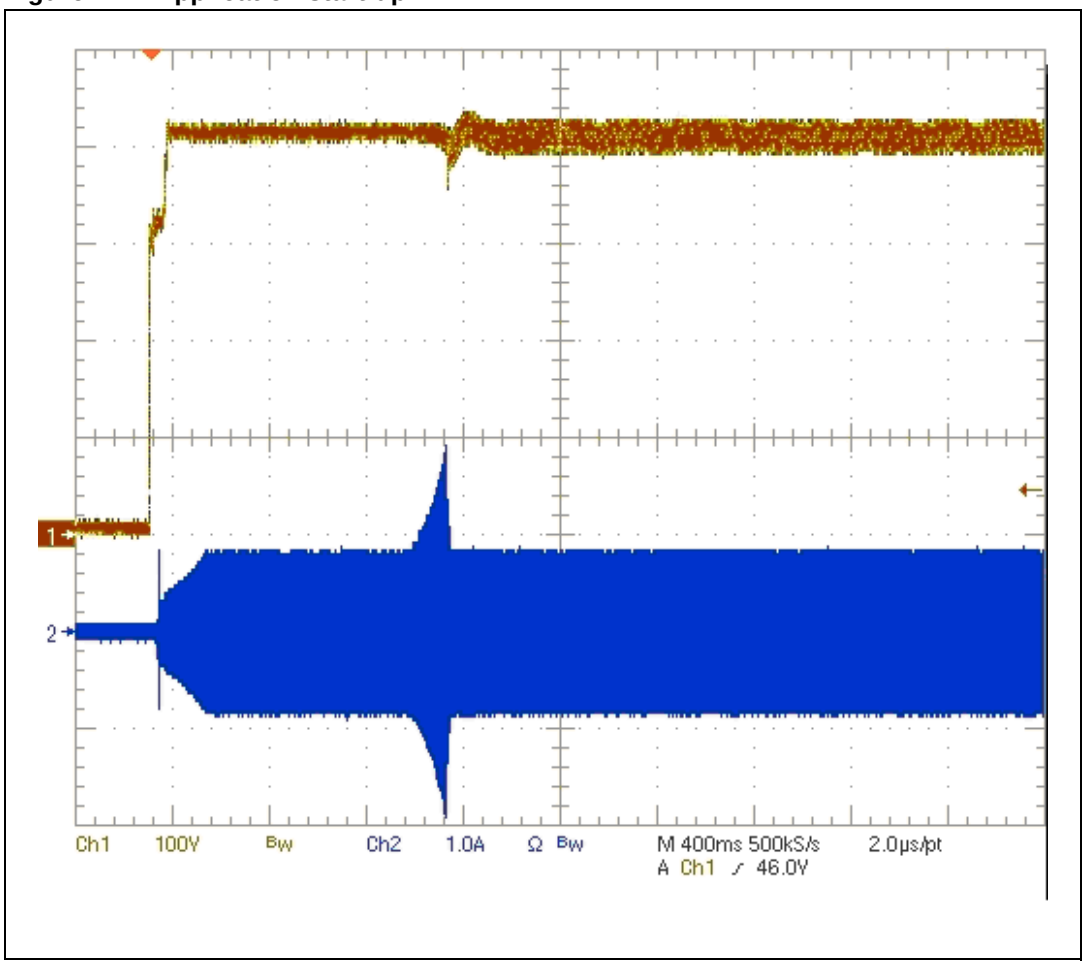


Figure 14 shows a DC bus voltage waveform during ballast turn-on. The precision of regulation during normal operation (lamp is on) is ±5%. The only moment when this accuracy is breached is at ignition phase, when there is a relative fast load change (lamp voltage and current rise quickly). It is assumed that by improving the regulation parameters, the ballast will also work from wide range mains (without any component change).

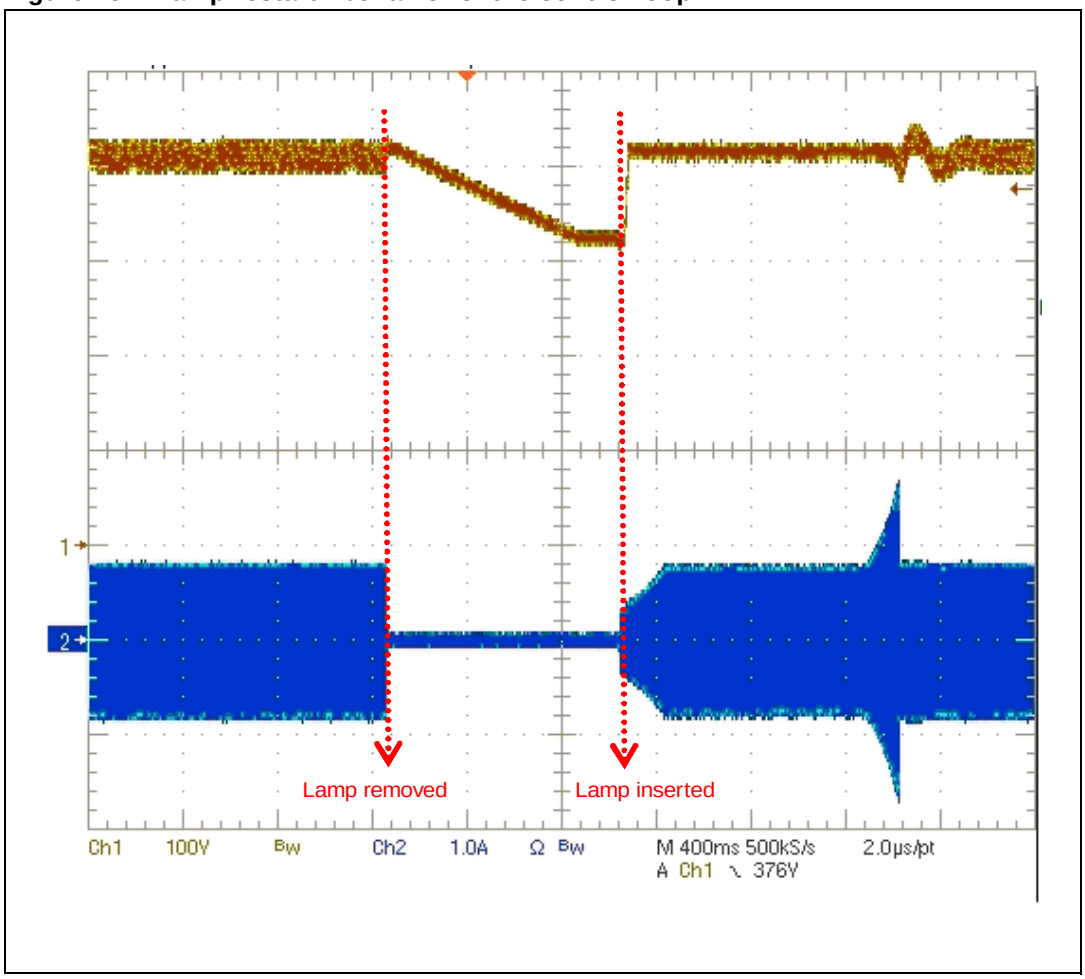
Figure 14. Application start-up



Note: Brown = $V_{DC\ BUS}$; Yellow = lamp current.

Beside the main control loop, output voltage is also used for protection. The software is continuously supervising the output voltage value and when it reaches the upper or lower threshold an error is detected. Overvoltage above the higher threshold could mean that there is an unexpected fast load reduction. Alternatively, breaking the lower threshold means a fast increase of the load. Both situation are considered dangerous and are recognized as faults.

Figure 15. Lamp restart - behavior of the control loop

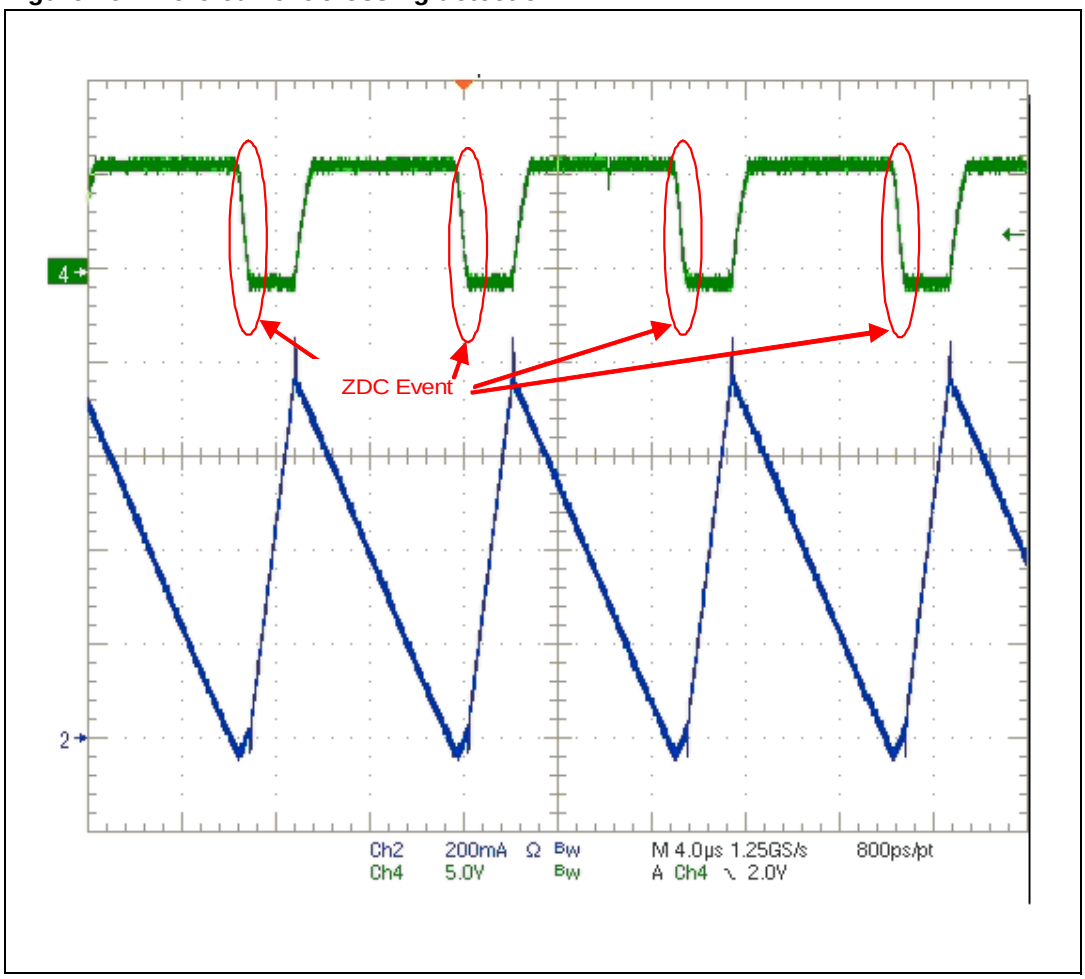


Note: Brown = DC bus voltage; Blue = lamp filament current.

4.3 Zero Current Detection

Detection of a zero current crossing the PFC inductor is extremely important. As described in *Section 2: Power Factor Correction (PFC)*, a ZCD defines the moment when the switch should be turned-on again. A well-known method used in other analog PFC applications has been implemented for the digital ballast. The secondary winding of PFC inductor (1:10 winding ratio) gives a correct signal for the autoreload timer (*Chapter 2.2*). Typical signals are shown in *Figure 16*.

Figure 16. Zero current crossing detection



Note: Green = microcontroller's input pin 18, Blue = inductor current.

4.4 MOSFET current measurement

The main reason for measuring a current flowing through the PFC MOSFET is to prevent exceeding the maximum current rating and so saturating the boost inductor which results in damaging components.

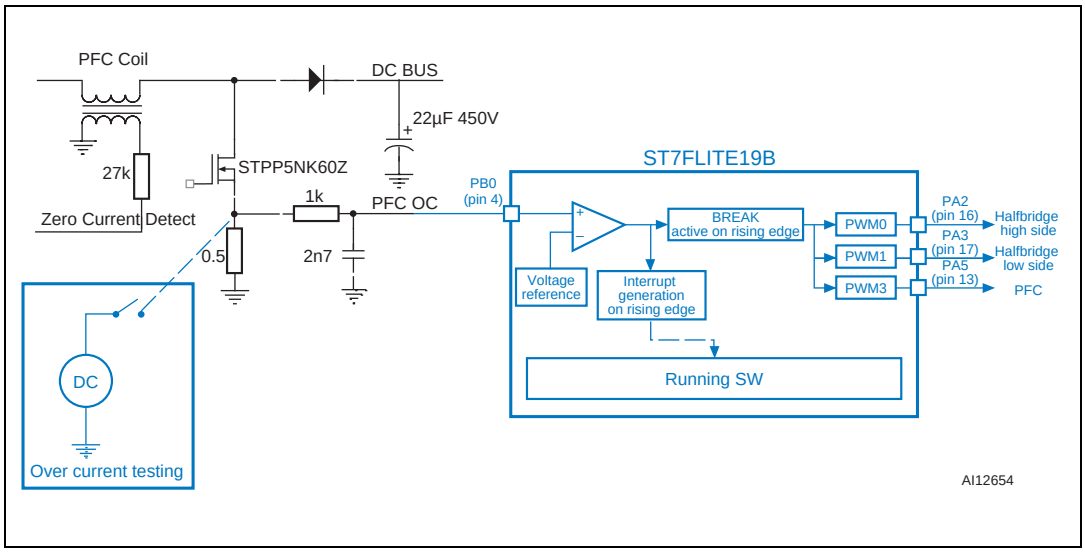
The software routines in general are too slow to perform fast reaction. For this reason, only hardware peripherals are used, and the software is excluded from the detection of over-current. Two extra features of the ST7LITE19B are important for this protection:

- the analog comparator;
- the break function.

The comparator integrated inside the microcontroller (datasheet ST7Lite1xB, *4* section 11.6) is a general purpose analog comparator with either an external or internal reference. Output can be seen on an external pin (Port PA7 - pin 11), or as it is in this case used only internally as an input for the second peripheral - the Break.

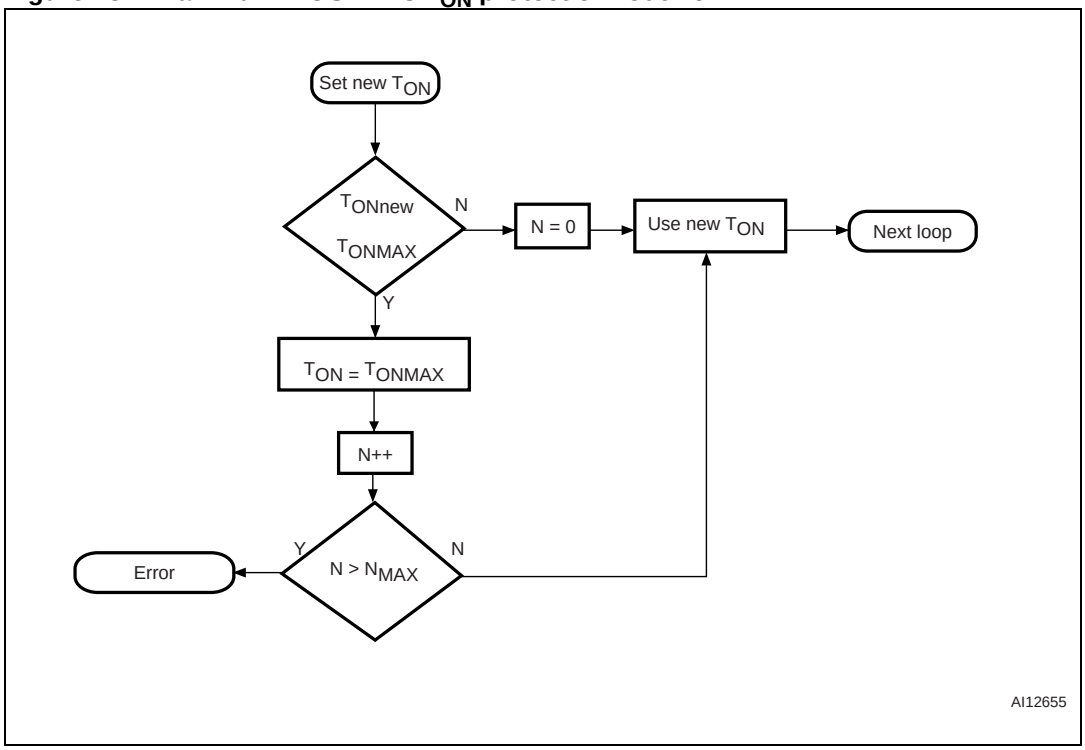
The Break function is an emergency shutdown used to stop all PWM outputs (i.e. MOSFET gate signals). A detailed description of it may be found in the ST7FLITE19B datasheet, *4* section 11.2.3.3.

Figure 17. PFC MOSFET overcurrent detection circuit and zero coil current detection circuit with indicated testing connection and microcontroller inner structure



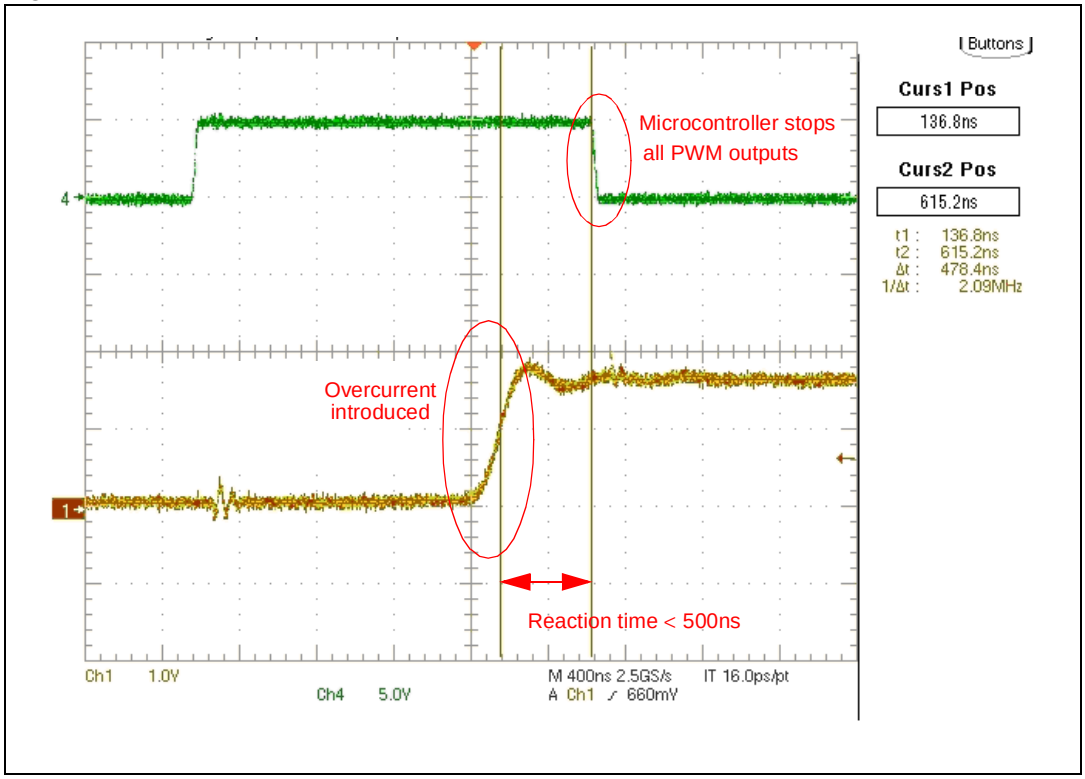
In order to simulate the PFC MOSFET overcurrent without stressing other components of the digital ballast, an external DC source has to be connected in parallel with the sense resistor R9 (0.5Ω). Afterwards, the MOSFET´s gate signal is measured, and the protection response time may be obtained, as shown in *Figure 19*. Such a response time was measured in less than 500ns, which is fast enough to prevent coil saturation and thereby protect the MOSFET from damage.

Figure 18. Maximum MOSFET's T_{ON} protection routine



In addition to the aforementioned hardware protections, another safety feature (Maximum T_{ON} increase protection) is implemented in the software and outlined in *Figure 18*. During normal operation, the PFC routine counts the number of times the pre-set MOSFET's on-time maximum (T_{ONMAX}) is reached. If the maximum count(N_{MAX}) is exceeded an error is introduced and the application is stopped. This condition indicates that the boost converter is unable to reach the required output voltage.

Figure 19. Overcurrent reaction demonstration



Note: Brown = sense resistor voltage, Green = digital signal for driving MOSFET's gate.

5 Conclusion and outlook

This application note explains the power factor correction (PFC) stage of the new digital ballast reference design. It demonstrates a synergy between the power management unit L6382D5 and the 8-bit microcontroller ST7FLITE19B in a fully digitally controlled application. The reference design STEVAL-ILB002V1 is introduced with all the features and protections required for high performance digital power supplies/ electronic ballasts. Additional flexibility through the use of a digital approach has been highlighted as well.

The document AN1971 (*2*) could be referred for more information on first implementation of a digital ballast with control based on the ST7Lite09. Other application notes for full digital ballast (reference design STEVAL ILB002V1) are published in two further application notes.

6 References and related materials

1. A. Loidl: "Digital ballast with PFC for Fluorescent Tube Lamps fully digitally controlled by 8-bit microcontroller", PCIM 2006.
2. STMicroelectronics, AN1971 ST7LITE0 Microcontrolled ballast, *http://www.st.com/stonline/products/literature/an/10534.pdf.*
3. STMicroelectronics, AN966 L6561, Enhanced Transition Mode Power Factor Corrector, *http://www.st.com/stonline/products/literature/an/5408.pdf.*
4. STMicroelectronics, ST7Lite1xB datasheet, *http://www.st.com/stonline/products/literature/ds/11929/st7lit19bf1.pdf.*
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6. IEC 61000-3-2 "Electromagnetic compatibility".
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Appendix A Components calculation

This appendix presents guidelines for the calculation of power components. The content is based on the design process defined in AN966 (*3*).

A.1 Input capacitor

The input high frequency filter capacitor (C_3) has to attenuate the switching noise due to the high frequency inductor current ripple (twice the average line current, *Figure 9*). The worst conditions occur on the peak of the minimum rated input voltage. The maximum high frequency voltage ripple is usually imposed between 1% and 10% of the minimum rated input voltage. This is expressed by a coefficient 'r' (typically, r = 0.01 to 0.1):

$$C_3 = \frac{I_{RMS}}{2\pi \bullet f_{SW} \bullet r \bullet V_{irms\ (min)}}$$

High values of C_3 alleviate the burden to the EMI filter but cause the power factor and the harmonic contents of the mains current to worsen, especially at high line and light load. On the other hand, low values of C_3 improve power factor and reduce mains current distortion but require heavier EMI filtering and increase power dissipation in the input bridge. It is up to the designer to find the right trade-off in their application.

A.2 Output capacitor

The output bulk capacitor (C_o) selection depends on:

- the DC output voltage;
- the admitted overvoltage;
- the output power;
- the desired voltage ripple.

A voltage ripple (ΔVo = 1/2 ripple peak-to-peak value) of 100 to 120Hz (twice the mains frequency) is a function of the capacitor impedance and the peak capacitor current ($I_{C(2f)pk}$ = Io):

$$\Delta V_O = I_O \bullet \sqrt{\frac{1}{(2\pi \bullet 2f \bullet C_O)^2} + ESR^2}$$

With a low ESR capacitor the capacitive reactance is dominant, therefore:

$$C_O \geq \frac{I_O}{4\pi \bullet f \bullet \Delta V_O} = \frac{P_O}{4\pi \bullet f \bullet V_O \bullet \Delta V_O}$$

ΔV_o is usually selected in the range 1 to 5% of the output voltage. Although ESR usually does not affect the output ripple, it has to be taken into account for power loss calculations. The total RMS capacitor ripple current, including mains frequency and switching frequency components, is:

$$I_{Crms} = \sqrt{\frac{32\sqrt{2}}{9\pi} \bullet I_{rms}^2 \bullet \frac{V_{irms}}{V_o} - I_o^2}$$

If the application has to guarantee a specified hold-up time, the selection criterion of the capacitance will change: C_o has to deliver the output power for a certain time (t_{Hold}) with a specified maximum dropout voltage:

$$C_O = \frac{2 \bullet P_O \bullet t_{Hold}}{V_{o_min}^2 - V_{op_min}^2}$$

where V_{o_min} is the minimum output voltage value (which takes load regulation and output ripple into account) and V_{op_min} is the minimum output operating voltage before the 'power fail' detection from the downstream system supplied by the PFC.

A.3 Boost inductor

Designing the boost inductor involves several parameters and different approaches can be followed. First, the inductance value must be defined. The inductance (L) is usually determined so that the minimum switching frequency is greater than the maximum frequency of the internal starter, to ensure a correct TM operation. Assuming unity PF, it is possible to write:

$$T_{on} = \frac{L \bullet I_{Lpk} \bullet \sin(\theta)}{\sqrt{2} \bullet V_{irms} \bullet \sin(\theta)} = \frac{L \bullet I_{Lpk}}{\sqrt{2} \bullet V_{irms}} \qquad T_{off} = \frac{L \bullet I_{Lpk} \bullet \sin(\theta)}{V_O - \sqrt{2} \bullet V_{irms} \bullet \sin(\theta)}$$

T_{on} being the ON-time and T_{off} the OFF-time of the power MOSFET, I_{Lpk} the maximum peak inductor current in a line cycle and θ the instantaneous line phase ($\theta \in (0,\pi)$). Note that the ON-time is constant over a line cycle.

As previously mentioned, I_{Lpk} is twice the line-frequency peak current, which is related to the input power and the line voltage:

$$I_{Lpk} = 2 \bullet \sqrt{2} \bullet \frac{P_i}{V_{irms}}$$

Substituting this relationship in the expressions of T_{on} and T_{off}, after some algebra it is possible to find the instantaneous switching frequency along a line cycle:

$$f_{sw}(\theta) = \frac{1}{Ton + Toff} = \frac{1}{2 \bullet L \bullet P_i} \bullet \frac{V_{irms}^2 \bullet \{V_o - \sqrt{2} \bullet \sin(\theta)\}}{V_o}$$

The switching frequency will be minimum at the top of the sinusoid ($\theta = \pi/2 \Rightarrow \sin(\theta) = 1$), maximum at the zero crossings of the line voltage ($\theta = 0$ or $\pi \Rightarrow \sin(\theta) = 0$) where $T_{off} = 0$.

The absolute minimum frequency $f_{sw(min)}$ can occur at either the maximum or the minimum mains voltage, thus the inductor value is defined by:

$$L = \frac{V_{irms}^2 \bullet (V_o - \sqrt{2} \bullet V_{irms})}{2 \bullet f_{sw(min)} \bullet P_i \bullet V_o}$$

where V_{irms} can be either $V_{irms(min)}$ or $V_{irms(max)}$), whichever gives the lower value for L. Once the value of L is defined, the real design of the inductor can start. Standard high frequency ferrite (gapped core-set with bobbin) is the usual choice in PFC applications. Selection of the most suitable one, among the various types offered by manufacturers, will depend on technical and economic considerations.

The next step is to estimate the core size. To calculate an approximate value of the minimum core size, the following practical equation may be used:

$$Volume \geq 4K \bullet L \bullet I_{rms}^2$$

where Volume is expressed in cm^3, L in mH and the specific energy constant K depends on the ratio of the gap length (l_{gap}) and the effective magnetic length (l_e) of the ferrite core:

$$K \cong 14 \bullet 10^{-3} \bullet \frac{l_e}{l_{gap}}$$

The ratio l_e/l_{gap} is fixed by the designer.

Next, the winding has to be specified. Quantities to be defined include the turn number and the wire cross-section.

The (maximum) instantaneous energy inside the boost inductor (1/2 × L × ILpk^2) can be expressed in terms of energy stored in the magnetic field, given by the maximum energy density times and the effective core volume V_e:

$$\frac{1}{2} \bullet L \bullet I_{Lpk}^2 = \frac{1}{2} \bullet \Delta H \bullet \Delta B \bullet V_e \approx \frac{1}{2} \bullet \Delta H \bullet \Delta B \bullet A_e \bullet l_e$$

where: A_e is the effective area of the core cross-section, ΔH is the swing of the magnetic field strength and ΔB is the swing of the magnetic flux density.

An air gap needs to be introduced to prevent the core from saturating because of its high permeability and to allow an adequate ΔH.

Despite the fact that gap length l_{gap} is only a small per cent of l_e, the permeability of ferrite is so high (for power ferrites the typical value of μ_r is 2500) that it is possible to assume, with good approximation (ΔH » ΔHgap), that the whole magnetic field is concentrated in the air gap. For instance, with an l_{gap}/l_e value of 1% (which is the minimum suggested value) the error caused by the above assumption is approximately 4%. The error is smaller if the l_{gap}/l_e ratio is larger. As a result, the fringing flux in the air gap region may be neglected and the energy balance can be re-written as:

$$L \bullet I_{Lpk}^2 \approx \Delta H_{gap} \bullet \Delta B \bullet A_e \bullet l_{gap}$$

The flux density ΔB, is the same throughout the core and the air gap, and is related to the field strength inside the air gap by the well-known relationship:

$$\Delta B = \mu_0 \bullet \Delta H_{gap}$$

Then, taking Ampere's law into account (but applying it only to the air gap region):

$$l_{gap} \bullet \Delta H_{gap} \approx N \bullet I_{Lpk}$$

it is possible to obtain the following equation from the energy balance equation :

$$L \approx \mu_0 \bullet \frac{N^2 \bullet A_e}{l_{gap}} \Rightarrow N \approx \sqrt{\frac{L \bullet l_{gap}}{\mu_0 \bullet A_e}}$$

where N is the turn number of the winding.

Because N is defined, it is recommended to check the core saturation. If the core saturation result is too close to the rated limit, it will be necessary to increase the value of l_{gap} and make a new calculation.

The wire gauge selection is based on limiting the copper losses to an acceptable value:

$$P_{CU} = \frac{4}{3} \bullet I_{rms}^2 \bullet R_{CU}$$

Due to the high ripple frequency, the effective wire resistance $R_{CU,}$ increases by skin and proximity effects. For this reason litz wire or multi-wire solutions are recommended. Finally, the space occupied by the winding needs to be evaluated. If it does not fit the winding area of the bobbin, a bigger core set needs to be considered and the winding calculation repeated. It is also necessary to add an auxiliary winding to the inductor, in order for the ZCD pin to recognize at what point the current flowing through the inductor has fallen to zero. The winding is a low cost thin wire and the turn number is the only parameter to be defined.

A.4 Power MOSFET

The choice of MOSFET mainly concerns the R_{DSon}, which depends on the output power. The breakdown voltage is fixed by sum of the output voltage, the overvoltage and a safety margin .

The MOSFET's power dissipation depends on conduction and switching losses.

The conduction losses are given by:

$$P_{ON} = I_{Qrms}^2 \cdot R_{DSon}$$

where:

$$I_{Qrms} = 2 \cdot \sqrt{2} \cdot I_{rms} \cdot \sqrt{\frac{1}{6} - \frac{4\sqrt{2}}{9\pi} \cdot \frac{V_{irms}}{V_o}}$$

Switching losses due to current-voltage cross occur only at turn-off because of the TM operation:

$$P_{CROSS} = V_O \cdot I_{rms} \cdot t_{fall} \cdot f_{sw}$$

where t_{fall} is the crossover time at turn-off. At turn-on, loss is due to the discharge of the total drain capacitance inside the MOSFET itself. In general, these losses are given by:

$$P_{CAP} = \left(3.3 \cdot C_{OSS} \cdot V_{DRAIN}^{1.5} + \frac{1}{2} \cdot C_d \cdot V_{DRAIN}^2\right) \cdot f_{sw}$$

where C_{oss} is the internal drain capacitance of the MOSFET (at V_{DS} = 25V), C_d is the total external drain parasitic capacitance and V_{DRAIN} is the drain voltage at MOSFET turn-on. In practice, it is possible to give only a rough estimate of the total switching losses because both f_{sw} and V_{DRAIN} change along a given line half-cycle. V_{DRAIN}, in particular, is affected not only by the sinusoidal change of the input voltage but also by the drop due to the resonance of the boost inductor with the total drain capacitance. At low mains voltage, this causes V_{DRAIN} to be zero during a significant portion of each line half-cycle. It is possible to show that "Zero-Voltage-Switching" occurs as long as the instantaneous line voltage is less than half the output voltage.

A.5 Boost Diode

The boost freewheeling diode is a fast recovery one. Its respective DC and RMS current values, which are useful for loss computations, are given below:

$$I_{D0} = I_0$$

$$I_{Drms} = 2 \bullet \sqrt{2} \bullet I_{rms} \bullet \sqrt{\frac{4\sqrt{2}}{9\pi} \bullet \frac{V_{irms}}{V_o}}$$

The conduction losses can be estimated as follows:

$$P_{DON} = V_{to} \bullet I_{DO} + R_d \bullet I^2_{Drms}$$

where V_{to} (threshold voltage) and R_d (differential resistance) are parameters of the diode. The breakdown voltage is fixed with the same criterion as the MOSFET.

7 Revision history

Table 4. Document revision history

Date	Revision	Changes
17-Jan-2007	1	Initial release.

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